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A CONTRIBUTION TO THE IMPLEMENTATION OF ULTRAPRECISION ROTATIONS FOR MULTIAXIAL NANOPOSITIONING MACHINES

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ABSTRACT

Existing long range nanopositioning and nanomeasuring machines are based on three independent linear movements in three rectangular axes. This in combination with the specific nature of optical and mechanical sensors and tools limits the application of those machines in terms of addressable part geometries. State of the art multiaxial precision machines solve this problem but do not fulfil the requirements in positioning accuracy. This article contributes to the development of multiaxial machine structures allowing e.g. 5-axis operation while keeping the precision in the nanometre range. A parameter based dynamic evaluation system with quantifiable technological parameters is performed to identify general solution concepts. State of the art machines are evaluated based on this classification system in terms of the implementation of multi-axial movements. The evaluation system is further refined with comprehensive design catalogues and corresponding diagrams to support the selection of adequate substructures. First evaluations for the substructure in terms of a rotation axis for the probing system of a nanopositioning machine in its XZ-plane show the highest degree of fulfilment for basic structures considering a goniometer setup. After all, the knowledge gained is formed into general rules for the verification and optimization of constructive solutions for multiaxial nanopositioning machines.

Index Terms - multiaxial nanopositioning and nanofabrication, ultraprecision machine designs, advanced design principles of nanopositioning and nanomeasuring machines, ultraprecision rotations, design rules

1. INTRODUCTION

The majority of existing long range nanopositioning and nanomeasuring machines (NPMMs) are based on three independent linear movements in a Cartesian coordinate system with motion ranges up to the order of the magnitude of current maximum wafer size form the state of the art. The addressable volume advances up to 400 x 400 x 100 mm³ (xyz) with a repeatability below 100 nm (Table 1). Such machines show their limits in addressable part geometries of free-form surfaces with undercuts, high aspect ratios and steep surface angles since they allow only linear movements. An exceeding of the measurable surface angle is depending on the limitation of the tool in use (Figure 1).
For example, lateral resolutions of 20 nm are possible with the AFM sensor used in the nanopositioning and nanomeasuring machine of the Technische Universität Ilmenau. The measurable sample geometries of sensors are limited due to their form and volume, the working distances and other restrictions just like limited aperture angle of optical sensors, such as the focus sensor developed in Ilmenau. This leads to restrictions to the access of critical features (points of interest).

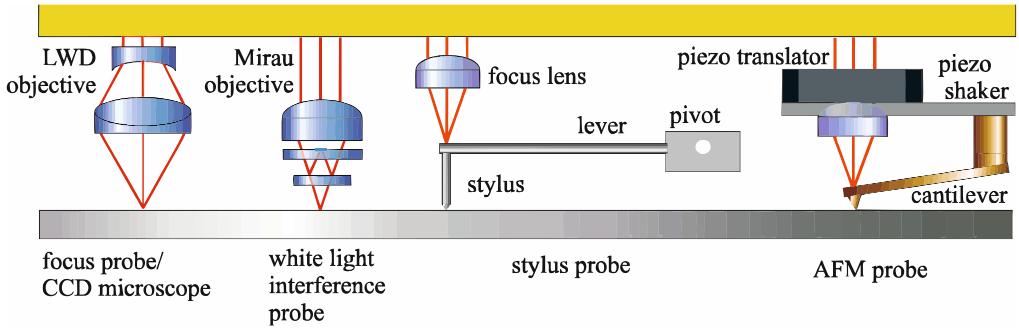

Figure 1. A selection of probing systems used in nanopositioning and nanomeasuring machines at the Technische Universität Ilmenau [1]

State of the art multiaxial precision machines with similar addressable volume solve this problem but do not fulfil the requirements in precision and intended rotation ranges of up to 360° for each rotation (Table 1).

Table 1 Examples of nanopositioning systems with 3 or more degree of freedom

nanopositioning system	operating range		repeatability
	translation (xyz) [mm]	rotation (θxθyθz) [mrad]	[±nm]/[±µrad]
NPMM200 [2]	200x200x25	-	≤ 30/-
ISARA400 [3]	400x400x100	-	≤ 109/-
NanoCMM [4]	50x50x4	-	≤ 38/-
Kang [5]	4x4x4	70x70x70	-
Hex500-350HL [6]	100x110x54	384x384x698	≤600/1
SmarPod Wafer 200 [7]	200x200x10	104x122x419	≤200/10

A significantly better access to geometry elements is made possible by the implementation of additional rotations to nanopositioning and nanomeasuring machines to create multiaxial machine structures allowing e.g. 5-axis operation while keeping the precision in the nanometre range. This article contributes to the systematic development of multiaxial machine structures in the early design state by varied combinations of overall machine structures with up to six degrees of freedom and extended rotation ranges. An evaluation system is presented which supports the user in the selection of machine structures fulfilling given requirements in the best possible manner.

2. Evaluation system for multiaxial NPMMs

To support the selection of machine structures for the development of a multiaxial nanopositioning machine, an evaluation system was developed. This is based on modular arrangement variants of basic components, a dynamic evaluation system and indications of the characteristics to be considered for the design process.

2.1 Basic structures of multiaxial NPMMs

The fundamental structures of nanopositioning and nanomeasuring machines are based on three modes of movement, the Sample Scanning Mode (SSM), the Mixed Scanning Mode (MSM) and the Scanning Probe Mode (SPM) (Figure2).

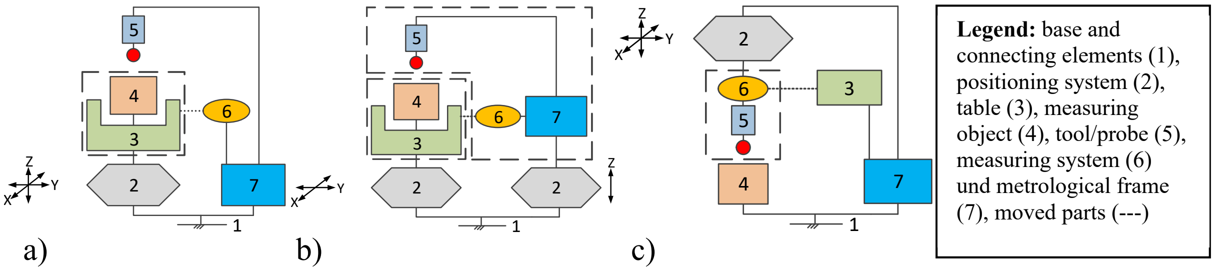

Figure 2. System configuration for the Sample Scanning Mode (a), Mixed Scanning Mode (b) and Scanning Probe Mode (c) [2]

These three basic scanning modes differ primarily in the respectively moved components. Thus in the NPMM200 (Table 1), that is based on the Sample Scanning Mode, the object is moved together with a table in three linear axes of a Cartesian coordinate system.
The geometries of the objects can be measured using probe systems, which are attached to a shared metrological frame. In the case of the ISARA400 (Table 1), the measuring system for the z-axis and the probe are connected to a shared moving frame separated from the x-y table. Both variants are in compliance to the Abbe Comparator Principle. Characteristic of the Mixed Scanning Mode variant are a high moving mass in z-direction. Based on the three basic scanning modes, further variations are possible for the modular design of multiaxial nanopositioning systems. E.g., the arrangement of the measuring system and the table can be varied in relation to the moved module (Figure 3).

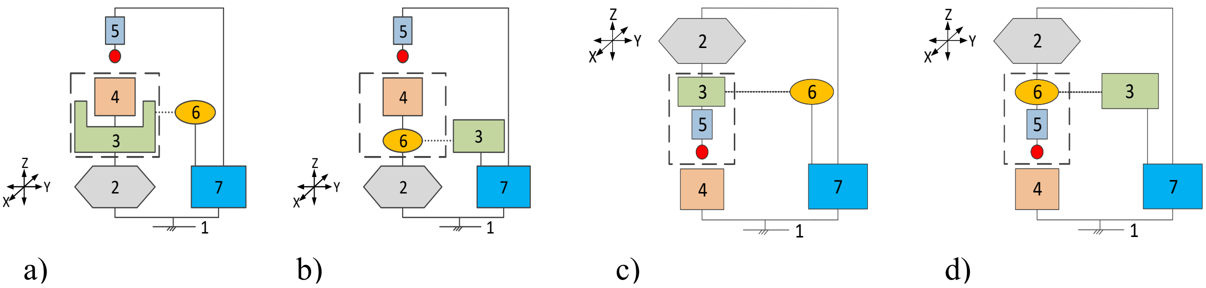

Figure 3. First step of varying the basic elements: arrangement of measuring system and table

Examples of the Scanning Probe Mode with resolution in the nanometre range are the Luphoscan [8] by Taylor Hobson and the Non-contact Measuring Machine for Freeform Optics from the Technische Universiteit Eindhoven [9]. The challenge is the realization of full compliance to the Abbe Comparator Principle for this mode. Corresponding properties, which are to be considered for a realization of a multiaxial nanopositioning and nanomeasuring system, are stored for the modular arranged design variants in the evaluation system. A further variation of the basic structures illustrated in Figure 3 is possible by varying the number and arrangement of measuring systems and moving tables. As exemplarily shown in Figure 4 for the Scanning Probe Mode, the translational and rotational motions can this be detected by the measuring system at a common table or at a separated table for each movement. This separation is necessary, for example, if an already existing design is upgraded by additional rotations and the existing measuring system is not suitable for this purpose. The described modular arrangements are feasible for all scanning modes. Thus, at least 232 combinations are theoretically feasible solutions in up to six degrees of freedom. The number of combinations is calculated by combining all possible variations.

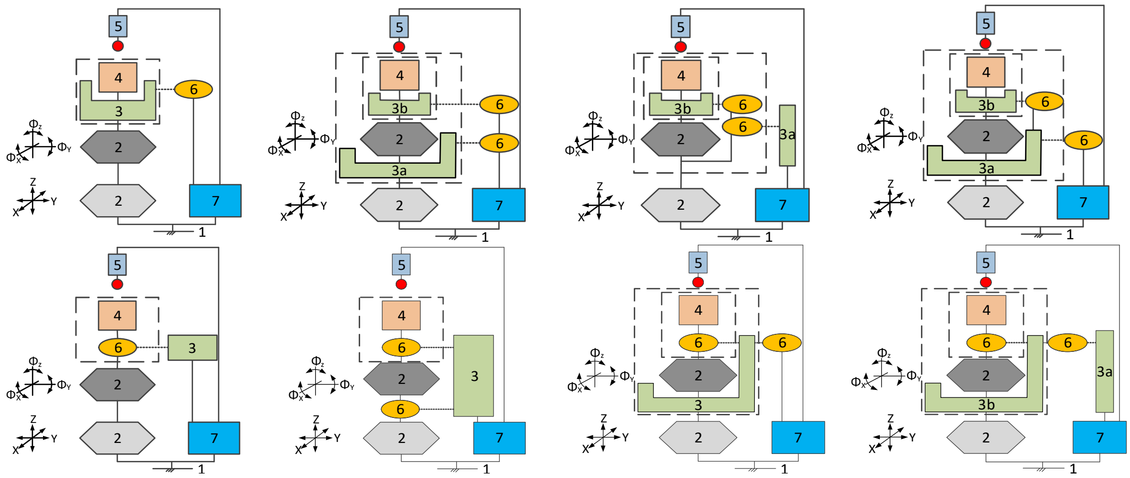

Figure 4. Second step of varying the basic elements: number and arrangement of measuring systems and tables

An evaluation algorithm is required to support the systematic assessment of structures fulfilling the defined functional requirements.

2.2 Dynamic evaluation algorithm

In order to select the system suitable for the user out of the multiplicity of feasible modular arrangements, a weighted evaluation of the respective properties is done for the structural variants previously selected (Figure 5).

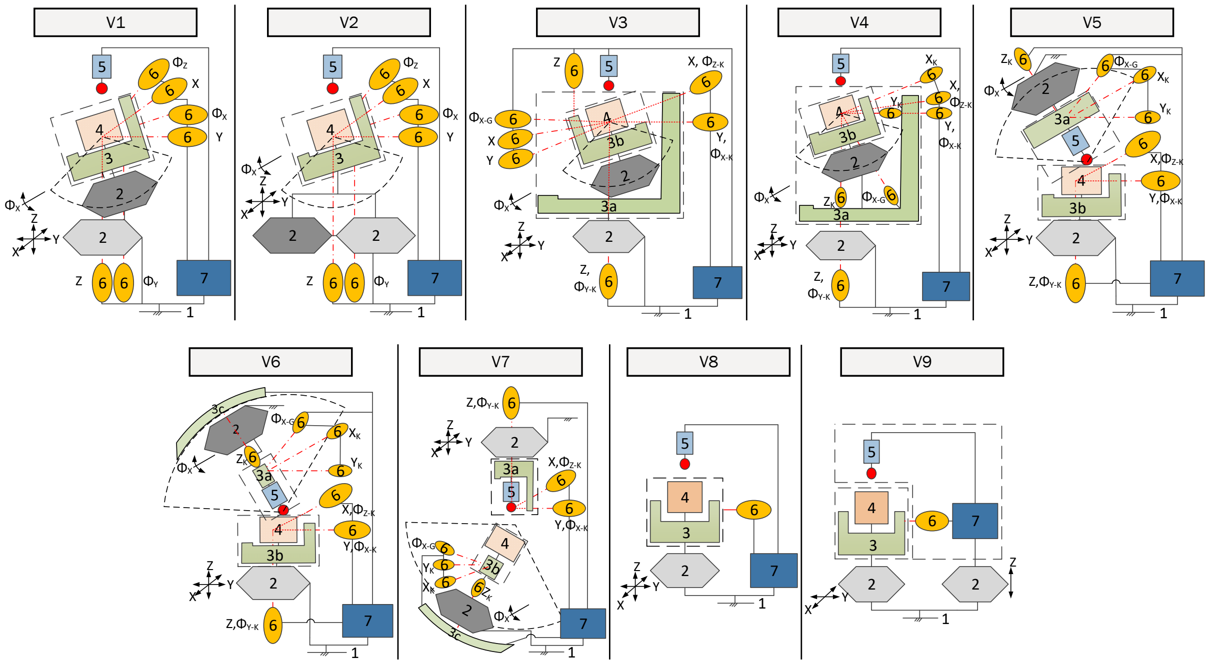

Figure 5. Structural sketches of selected structural variants

The user first selects the criteria to be used for the evaluation. Quantitative and qualitative as well as absolute and relative criteria are applicable for this purpose. For example, knowledge based assignment of masses can be applied by the user to the substructures to find the system with the smallest mass to be moved. Alternatively, the evaluation is determined by knowledge already stored in the system. E.g., a system variation, where the table has to carry an additional positioning system instead of just the measuring object itself will cause a change in the scores

given while the restrictions on the object remain untouched. The scoring is done based on an equally spaced scale in between the minimum and maximum moving mass.
Once the scoring is done to the properties to be compared, these are weighted by factors and combined to an overall evaluation. The user has the choice between a manual input of the weighting factors and a dynamic cross-comparison of all individual criteria. Depending on the desired weighting factors, a degree of fulfilment of the desired properties can be derived (Figure 6).

Evaluation of the structural variants																				
Structural variant / **Evaluation criterion**	Weighting	V1		V2		V3		V4		V5		V6		V7		V8		V9		Max. pt
		pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	
Avoiding first-order errors	12	4	48	4	48	4	48	4	48	4	48	4	48	4	48	3	36	2	24	6
Degree of freedom of the measuring point	10	4	40	4	40	4	40	4	40	4	40	4	40	4	40	3	30	3	30	6
Rotation range	5	2	10	2	10	5	25	5	25	5	25	5	25	4	20	1	5	1	5	6
Use of basic NPMM principles	4	6	24	5	20	3	12	1	4	3	12	2	8	2	8	6	24	1	4	6
Smallest mass to be translated	7	3	21	6	42	1	7	0	0	4	28	4	28	5	35	5	35	0	0	6
Moment of inertia (about main rotation)	7	0	0	0	0	4	28	4	28	2	14	2	14	1	7	6	42	6	42	6
Moment of inertia (about X and Y axes)	4	5	20	5	20	2	8	2	8	5	20	5	20	6	24	5	20	0	0	6
Sum	49	24	163	26	180	23	168	20	153	27	187	26	183	26	182	29	192	13	105	
Fulfillment [%]	294		55,44		61,22		57,14		52,04		63,61		62,24		61,90		65,31		35,71	

Figure 6. Degree of fulfilment of selected structural variants

2.3 Extension of the evaluation system to select substructures

The parameter based dynamic evaluation system is further refined to support the selection of adequate substructures for multiaxial nanopositioning systems. For this purpose, the basic components can be differentiated further in substructures, according to [10] (Figure 7).

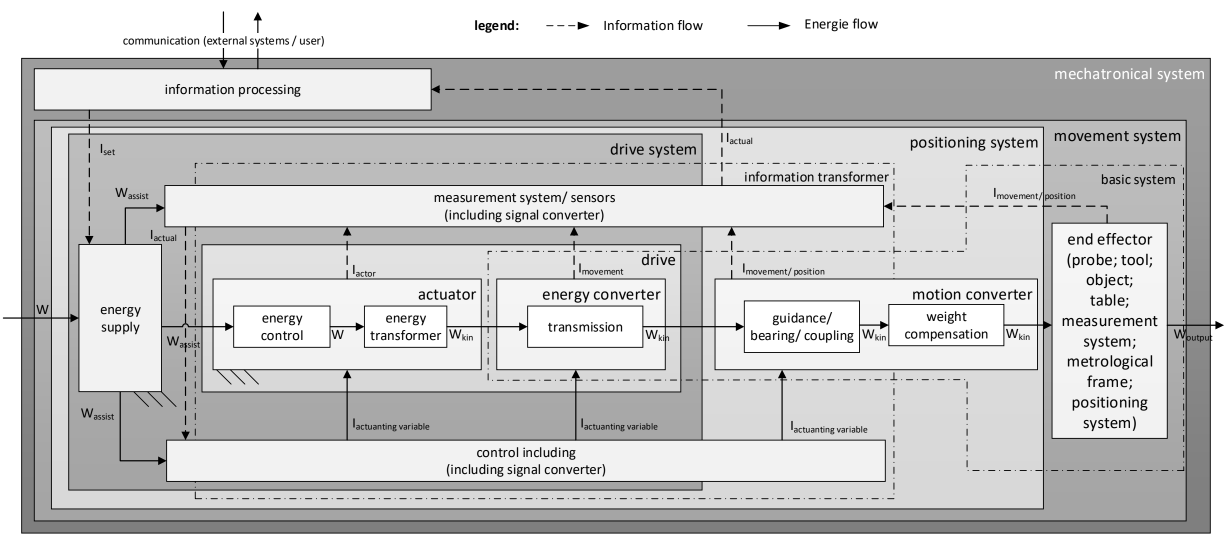

Figure 7. Mechatronic positioning system for typical end effectors in NPMMs

For example, a suitable positioning system can be combined from actuators, transmissions, guides and coupling elements in order to control the movement of an end effector.
A large number of technical implementations are possible for these substructures. In order to support the user in the selection of suitable components for multiaxial nanopositioning and nanomeasuring machines, the evaluation system contains comprehensive design catalogues with solution variants for:

- Positioning systems
- Actuators
- Guides and bearings
- Measuring systems

The individual design catalogues are divided successively into:

- General, coordinating comparison of basic guiding and bearing principles;
    - Basic structure and arrangement principles (e.g. serial, parallel or hybrid kinematics)
    - Design variants (e.g. ball-, slide-, hydrostatic- and aerostatic bearings)
- Parameter comparison of relevant properties of different principles and design variants
    - General principles comparison (e.g. accuracy, stiffness, friction, durability of ball-, slide-, hydrostatic- and aerostatic bearings)
    - Comparison of specific design variants (e.g. accuracy, stiffness, friction, durability of deep grooved-, angular-, self-aligning- und axial grooved ball bearings)
- Specific characteristic profiles (e.g. manufacturer comprehensive design catalogues with quantitative properties of diverse positioning systems, actuators and measuring systems related to ultra-precise positioning and measuring technology)
- Overview of components and solutions already used in nanopositioning and nanomeasuring machines

2.4 Support for the selection of a suitable substructure using the example of a rotation axis for the probing system of a nanopositioning machine

In order to support the selection of an applicable positioning system for the rotation of a probe as an extension of the nanopositioning and nanomeasuring machine of the Technische Universität Ilmenau [2], the following selection process would result.

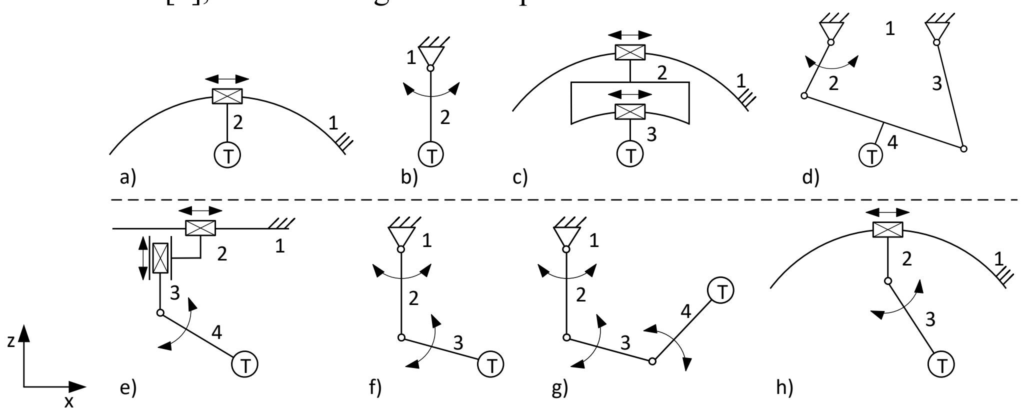

Figure 8. Selection of mechanism structures of rotations in the XZ-plane of a NPMM with the respective number of elements of the kinematic chain and the tip of the probe (T)

The selection of a suitable positioning system for the rotation of the touch probe can be started with the selection of a basic mechanism structure, stored in the evaluation system (Figure 8). These basic mechanism structures are varied in terms of:

- The number and angular offset of the rotation planes (e.g., rotations in Figure 8 only in one plane)
- The position of the instantaneous centre of rotation (e.g., in the tip of the probe of the goniometer in Figure 8a and in the base frame of the pendulum in Figure 8b)
- The distribution of the range of movement (e.g., one large positioning system in Figure 8a and large- and fine positioning systems in Figure 8c)
- The setup of motion kinematics (e.g., serial in Figure 8f and parallel in Figure 8d)
- The compensation of translational parts of the rotation by additional translational positioning systems (e.g., Figure 8e)

The process of the selection of a suitable rotation system can be continued by choosing a specific positioning system that fulfils the given requirements. To support this selection process, design catalogues with comprehensive data sets of different manufacturers for ultra-precise rotation systems are stored in the evaluation system.

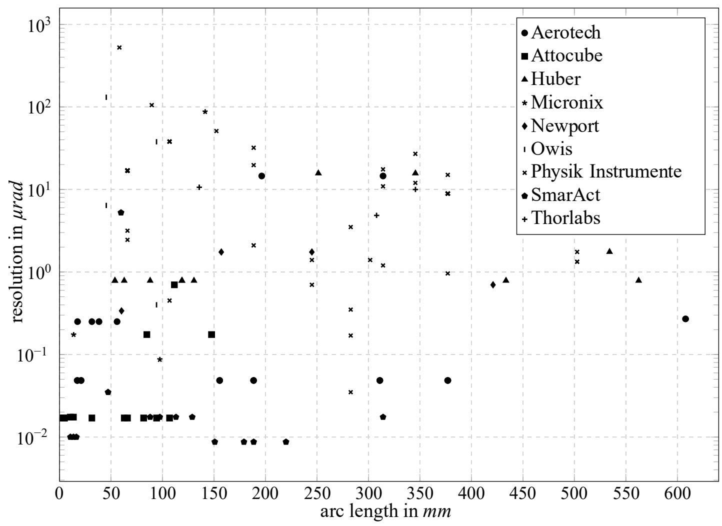

Figure 9. Selected rotation positioners of different manufacturers for the rotation of a probe in the XZ-Plane of a NPMM

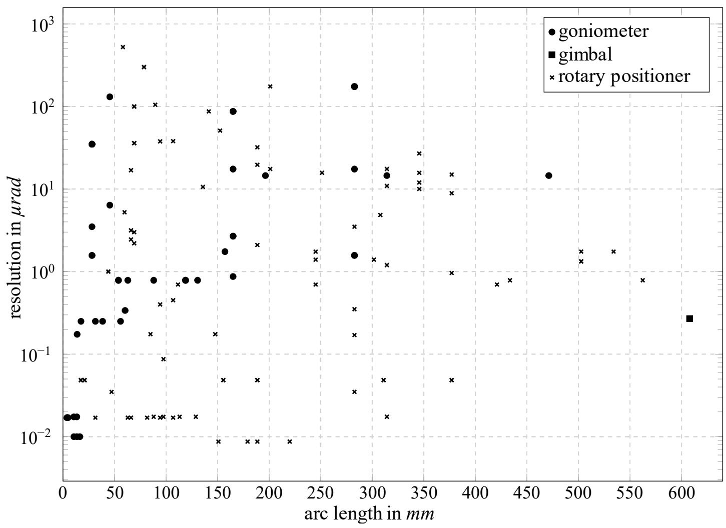

Figure 10. Selected mechanism structures of different manufacturers for the rotation of a probe in the XZ-Plane of a NPMM

Evaluation diagrams which compare these systems with regard to the angular resolution, the movement range, the mechanism structure, the drives and the bearings are stored in the system (e.g. Figure 9 and Figure 10).
The application of the evaluation diagrams and design catalogues can be used to select a feasible system that meets the previously given requirements. If the requirements cannot be fulfilled by existing substructures, tendencies for new or further development of suitable structural variants can be derived based on the given information set. In conjunction with a dynamic evaluation system for the mechanism structure, a suitable solution can be developed iteratively.
This is carried out after the choice of the feasible mechanism structure as a modular arrangement of elements of the substructure design catalogues.
The selection of a suitable mechanism, as for the selection of the overall structure (chapter 2.2), is supported by corresponding characteristics profiles and the dynamic evaluation algorithm.
In contrast to the selection of the overall structure, the implemented evaluation criteria are changed (Figure 11). For the implementation of rotations to the existing periphery of a NPMM it is, for example, of great importance if the resulting rotation range is restricted, where the instantaneous centre of rotation is located and if correction movements by linear positioning systems are necessary.

Evaluation of the mechanism variants

Structural variant / Evaluation criterion	Weighting	V1 (a)		V2 (b)		V3 (c)		V4 (d)		V5 (e)		V6 (f)		V7 (g)		V8 (h)		Max. pt
		pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	pt	W. pt	
Correction movement required	9	4	36	2	18	4	36	2	18	4	36	2	18	2	18	2	18	4
Complexity of the mechanism	8	3	24	4	32	3	24	3	24	2	16	3	24	2	16	3	24	4
Extensionpotential of the principle	7	3	21	3	21	2	14	2	14	3	21	3	21	3	21	2	14	3
Rotation range	11	3	33	1	11	3	33	1	11	4	44	2	22	3	33	4	44	4
Large- and fine positioning	2	0	0	0	0	4	8	0	0	0	0	0	0	0	0	0	0	4
Calculation of kinematics	2	3	6	4	8	2	4	1	2	2	4	2	4	1	2	2	4	4
Instantaneous centre of rotation	10	3	30	1	10	3	30	2	20	2	20	2	20	2	20	2	20	3
Sum	49	19	150	15	100	21	149	11	89	17	141	14	109	13	110	15	124	
Fulfillment [%]	179		83,80		55,87		83,24		49,72		78,77		60,89		61,45		69,27	

Figure 11. Degree of fulfilment of selected mechanism structures of rotations in the XZ-plane of a NPMM

Depending on the chosen weighting factors, a degree of fulfilment of the desired properties is derived for the selected mechanism structures (Figure 8 and Figure 11).

3. Conclusions

A parameter based dynamic evaluation system with quantifiable technological parameters is performed to identify general solution concepts for the overall structure and substructures of a multiaxial nanopositioning and nanomeasuring machine.
First evaluations for the overall structure show the highest degree of fulfilment for basic structures for a mixed mode with three translations of the sample separated from three rotations of the probe (V5 and V6 in Figure 5). This minimizes the mass and the moment of inertia of the main translational and rotational movements. The accessibility of points of interest

compared to existing NPMMs is increasing with the number of rotations while still strictly keeping the separation of the force frame and the metrology frame. The number of linear moving tables should be reduced to one with minimized mass and moment of inertia. The measuring systems should measure all linear movements directly on the object table. Tables should have a high stability according to thermal and mechanical influence to minimise the deviations of the position of the point of interest and the table position. A parallel in plane design for the moving systems decreases the moving mass and increases the structural stiffness as well as the positioning accuracy.
First evaluations for the substructure in terms of a rotation axis for the probing system of a nanopositioning machine in its XZ-plane show the highest degree of fulfilment for basic structures considering a goniometer setup.
However, this is dependent on the weighting factors selected by the user. If, for example, more value is set on a maximum range of movement, an instantaneous centre of rotation in the tip of the probe, goniometer variants should be considered. Simultaneously the instantaneous centre of rotation is set to be in the Abbe Point of the linear axes. Suitable solutions need to be found by combining substructures fulfilling the positioning reproducibility over the entire range of motion in the available space.
If, on the other hand, a limited complexity and calculation of the kinematics is of high relevance and the translational portion of the probe movement can be compensated by additional linear positioning systems in the required accuracy range, as with the already existing positioning system of the NPMM [2], a pendulum structure should be selected.
For this purpose, it must be analysed by combining suitable substructures if the desired restriction of the range of motion is acceptable for the implementation under space restrictions.
In order to support the user in the selection of suitable substructures for multiaxial nanopositioning and nanomeasuring machines, the evaluation system contains comprehensive design catalogues and corresponding evaluation diagrams.
The application of the evaluation diagrams and design catalogues can be used to select a feasible system that meets the previously given requirements.
The parameter based dynamic evaluation system will be further developed and refined in coming work.
An expansion is made by a calculation module of the necessary accuracies of the substructure elements as an intermediate step between the mechanism structures and substructures as well as the application for rotations in several planes of the probe and the object.
For the combination of the general structures of the rotation in one plane, taking into account the variation of the combinatorial (serial or parallel arrangement) and special forms of parallel kinematic arrangements (hexapod), an increased number of overall structures for the rotations in two planes is available, to be investigated.

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REFERENCES

[1] E. Manske, G. Jäger, T. Hausotte, “A Multi-Sensor Approach for Complex and Large-Area Applications in Micro and Nanometrology”, Measure, NCSLI 7 (2), pp. 44–50, 2012

[2] F. Balzer, Entwicklung und Untersuchungen zur 3-D-Nanopositioniertechnik in großen Bewegungsbereichen, Universitätsverlag Ilmenau, Ilmenau, 2014

[3] H. Spaan, R. Donker, I. Widdershoven, “ISARA 400: Development of an ultra-precision CMM for 3D measurement of large parts”, ASPE Spring Topical Meeting – Mechanical Metrology and Measurement Uncertainty, pp. 2802-2806, 2009

[4] J.K., van Seggelen, NanoCMM: A 3D Coordinate Measuring Machine with low moving mass for measuring small products in array with nanometer uncertainty, Technische Universiteit Eindhoven, Eindhoven, 2007

[5] D. Kang, D. Gweon, Development of flexure based 6-degrees of freedom parallel nano-positioning system with large displacement, Rev. Sci. Instrum. 83, p 1, 2012

[6] Aerotech Inc, HEX500-350HL, 2017, https://www.aerotech.com/media/2596619/hexgen%20hex500-350hl.pdf

[7] SmarAct GmbH, SmarPod Wafer 200, 2017, http://www.smaract.com/products/smarpod-hexapod/wafer-200

[8] Taylor Hobson Ltd, LuphoScan, 2017, http://www.taylor-hobson.com.de/products/33/64.html

[9] R. Henselmans, Non-contact Measurement machine for Freeform Optics, Technische Universiteit Eindhoven, Eindhoven, 2009

[10] T. Erbe, Beitrag zur systematischen Aktor- und Aktorprinzipauswahl im Entwicklungsprozess, Univ.-Verl. Ilmenau, Ilmenau, 2013

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